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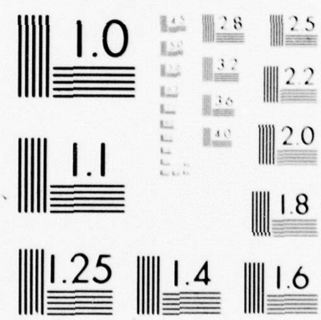

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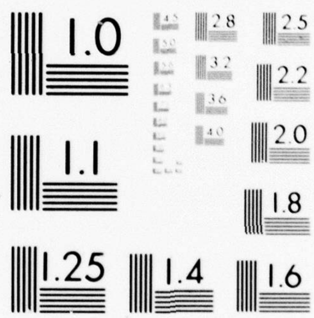

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Theoretical and experimental analyses have been conducted to examine both the steady-state and time-resolved characteristics of the mixing region between two coplanar, two-dimensional supersonic nozzles. In addition, an electron beam generator and associated optical measuring system have been assembled for use in CO_2 gas dynamic laser systems at the Air Force Weapons Laboratory.

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FLUID DYNAMIC INTERACTIONS IN MULTIPLE NOZZLE ARRAYS

Stuart L. Petrie
Department of Aeronautical and
Astronautical Engineering

For the Period
1 May 1973 - 30 September 1977

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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FOREWORD

This is the final technical report for the period 1 May 1973 through 30 September 1977 on Grant No. AFOSR-73-2537, "Fluid Dynamic Interactions Within Multiple Nozzle Arrays." Theoretical and experimental analyses have been conducted to examine both the steady-state and time-resolved characteristics of the mixing region between two coplanar, two dimensional supersonic nozzles. In addition, an electron beam generator and associated optical measuring system have been assembled for use in CO_2 gas dynamic laser systems at the Air Force Weapons Laboratory.

CONTENTS

I. INTRODUCTION

Supersonic chemical transfer lasers and mixing gas dynamic lasers have been the subject of considerable research in recent years because of the potentially large power available from such systems. In a typical arrangement for a chemical transfer laser, a gas containing fluorine is heated and expanded through a multiple array of small nozzles to supersonic Mach numbers. Alternate nozzle flows contain molecular hydrogen mixed with a diluent and the flows mix downstream of the nozzle exit. An exothermic chemical reaction occurs in the mixing layer between the two flows containing the molecular hydrogen and atomic fluorine atoms. Most of the heat of reaction is absorbed by the vibrational energy mode of the HF molecules formed and under proper conditions in a suitable cavity, these excited molecules can be made to lase.

Fluid mechanics plays a dominant role in the process of obtaining laser radiation from the lasing cavity for both chemical and gasdynamic laser configurations. Mixing phenomena at the jet boundaries influence the local species concentrations and density variations, which in turn determine the type of laser mode generated, the optical quality of the lasing medium, and the overall power output. The degree and scale of turbulence associated with the mixing process will also have an important effect on the optical quality of the lasing medium. Severe interactions between adjacent nozzle flows can create significant perturbations in the flow field. The investigation of the extent of both molecular and mechanical penetration of the inviscid nozzle flow into the mixing region is still considered to be state-of-the-art research for both chemical transfer and gasdynamic lasers.

Theoretical analyses of certain aspects of multiple nozzle laser configurations have advanced at a much more rapid rate than have corresponding experimental efforts. Emphasis in these theoretical studies has generally been placed on analyses of the reaction mechanisms in the fully mixed flow and the resulting effects on laser performance. The fluid mechanical details of the mixing process are usually handled by simple empirical correlations.

In early work by Mirels and co-workers a "flame sheet model" was employed to account for mixing. In this case, streamlines containing the flows to be mixed are assumed to intersect along the flame sheet. Laminar and turbulent diffusion are treated with this model by varying the scaling constants over roughly an order of magnitude. However, the flame sheet approach masks all the fluid mechanical phenomena; lateral diffusion of reaction products across stream tubes is neglected and axial velocity and pressure are assumed constant throughout the flow field. In more recent work, parallel mixing problems have been treated with turbulent transport coefficients described generally by algebraic eddy viscosity models.

Analysis of laser cavity flows is but one subset of a larger problem generally termed "turbulence modeling". Progress in such modeling can be developed only with heavy reliance on experimental data. However, as modeling proceeds from simple algebraic eddy viscosity models to higher order closure schemes, more demands are placed on the experimental programs if they are to produce results which can guide the modeling. For example, in simple mixing flows pressure measurements allow some assessment of the accuracy of a specific turbulence model but do not provide sufficient detail to allow improvement of the model. Ideally, both time averaged and fluctuating fluid properties should be measured in a single experiment. Time-resolved measurements within the mixing region or in the laser cavity are only now reaching the published literature.

In several previous experimental studies, attempts were made to assess the importance of various fluid mechanical influences, such as instabilities, mixing layer gradients and turbulence levels on the mixing layer structure. However, it appears that no systematic experimental investigation has been made to establish relative fluid mechanical influences in a configuration devoid of sophisticated injection techniques (e.g., trip geometry), complex chemical reactions and other interactions which complicate the verification of the assumptions inherent in more advanced theoretical analyses. Previous experimental efforts have invariably raised additional questions concerning very fundamental aspects of the investigations and complete documentation of the overall flow field is often lacking. Basic questions concerning mixing layer phenomena inherent in both chemical transfer and mixing gasdynamic lasers remain essentially unresolved.

The overall objective of the research reported here is to provide characterization of the fluid dynamical aspects of the laser mixing layers to permit assessment of the relative influences of parameters such as turbulent scale, energy spectrum and density fluctuations, as examples. A versatile experimental facility has been assembled and experimental techniques have been developed to establish the steady state and certain of the time resolved gasdynamic flow properties to allow investigations of the microstructure of mixing shear layers. Supporting theoretical analyses have also been conducted which allow variation of the turbulence model employed to characterize the mixing within the shear layer.

These studies are concerned primarily with the fluid mechanical aspects of gas flow lasers, and do not involve considerations of the lasing process. However, certain of the experimental techniques which have been developed during the course of this research are being applied in laser facilities at the Air Force Weapons Laboratory (AFWL). Summaries of the theoretical and experimental research conducted at OSU and the supportive experimental programs conducted at AFWL are given below.

II. EXPERIMENTAL PROGRAM

A. TEST FACILITY

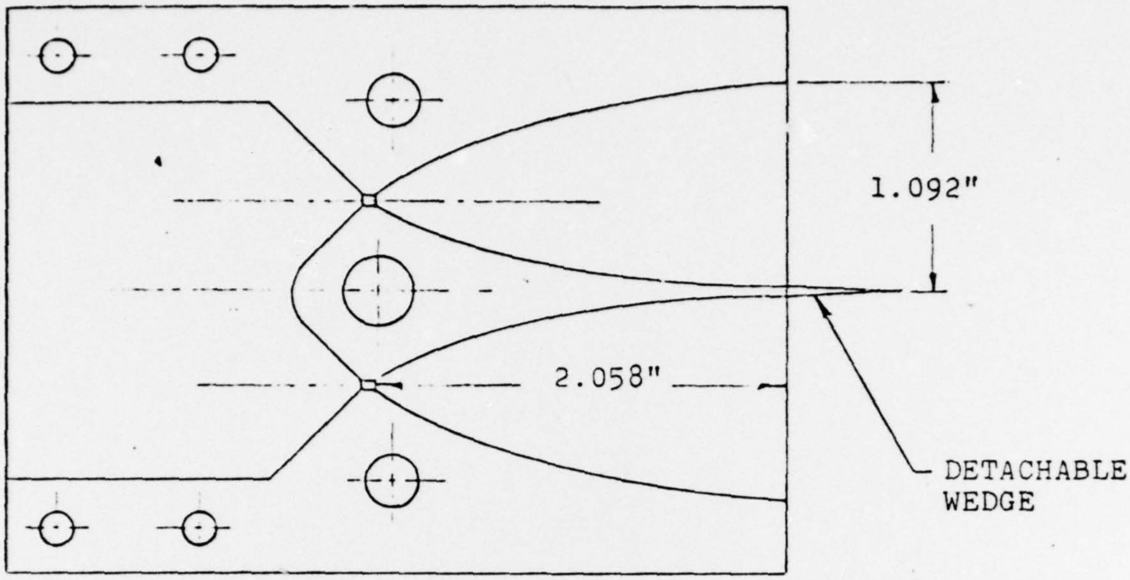
The experimental studies were conducted in a continuous flow, direct current arc heated wind tunnel facility. The arc heater was designed to provide a heated gas with a minimum of both electrode erosion and arc instability. Electrical power for the facility is supplied by two motor generator sets with a maximum continuous output power of 1.14 megawatts.

After passing through the arc heater the test gas enters a long plenum-transition reservoir, where temporal and spatial variations in gas properties are damped. The reservoir includes provisions for the mixing of cold test gas with the arc heated gas to obtain temperatures more nearly representative of present chemical and gasdynamic mixing lasers. From the reservoir region, the test gas enters a two dimensional nozzle configuration and then passes through an open jet test cabin to a water cooled diffuser system.

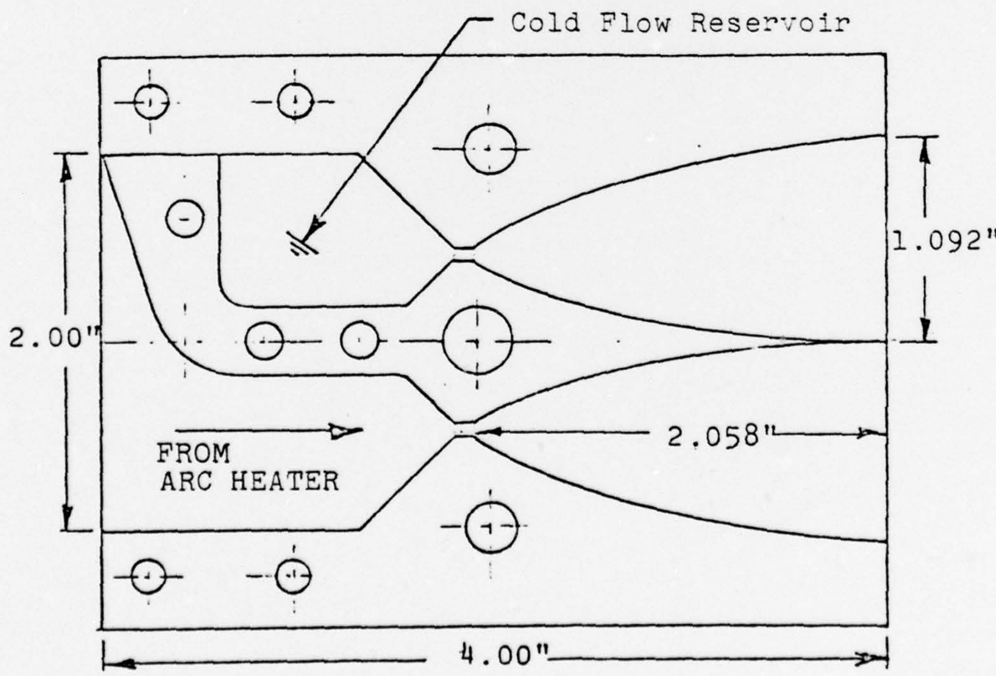
Two overall nozzle configurations are employed as shown in Figure 1. In the baseline configuration (Figure 1a) both nozzles are supplied from the arc heater reservoir. In the two stream system, one nozzle is supplied by the arc heater reservoir while the other is separately supplied with an arbitrary unheated gas. The latter configuration allows simulation of the large velocity and temperature differences which exist across adjacent nozzles in current chemical transfer lasers. Both contoured and wedge nozzle blocks are available for both configurations. In addition, the center nozzle element was designed for ease of replacement to allow a variety of mixing layer injection schemes to be investigated and the nozzle block holder permits rapid alteration of the nozzle array configuration for different Mach numbers or internal injection methods. To date, experimental studies have been conducted only with the baseline configuration with a nominal exit Mach number of 4.0. Operating with either air or molecular nitrogen, typical reservoir pressures and temperatures are 1.0 atm. and 2000°K, respectively. These conditions lead to flow properties at the nozzle exit which simulate those in supersonic flow chemical lasers of current interest.

B. INSTRUMENTATION

An electron beam provides the primary instrumentation system for analysis of the mixing region. In this technique, a narrow beam of electrons is projected across the flow and the interaction of the electrons with gas particles produces a column of radiation which is nearly coincident with the electron beam. High beam voltages (20 kv) are employed to obtain good spatial resolution. The beam is projected through the flow field in a direction perpendicular to the gas velocity. Profiles of gas properties are



a) Baseline Nozzle



b) Two Stream Nozzle

FIGURE 1. NOZZLE CONFIGURATIONS

obtained by examining various points along the length of the electron beam and measurements are made at various stations downstream of the nozzle exit. The spatial resolution of the measurements in the flow direction is limited by the minimum diameter of the electron beam (2 mm). The resolution in the direction perpendicular to the mixing layer (parallel to the electron beam) is determined by the field of view of the optical system employed to collect the electron beam-induced radiation. Extensive optical optimization studies have been conducted to obtain a spatial resolution near .010 inches.

When operating with air as the test gas, radiation is observed due to bombardment of molecular nitrogen, molecular oxygen, atomic oxygen, and nitric oxide. The predominant radiation is due to excitation of molecular nitrogen in the first negative system of the ionized nitrogen molecule. The most intense band in this system is the (0,0) band at 3914Å. Spectroscopic analysis of this radiation typically leads to measurements of the rotational temperature, vibrational temperature, and number density of the molecular nitrogen. The rotational temperature is assumed equal to the gas translational temperature. This assumption is valid because of the rapid equilibration of the rotational and translational degrees of freedom. Under extreme conditions, such as in a low density free jet expansion with a light gas (e.g. H_2), rotational nonequilibrium may be observed. However, for the condition of these studies, such nonequilibrium can be ignored.

In conventional applications of an electron beam, only the steady state gas properties are measured. However, during the course of the present studies theoretical and experimental analyses have been conducted to allow isolation of the rotational temperature turbulence, independent of fluctuations in other gas properties and electron beam operating parameters. This technique allows direct measurement of the temperature turbulence at arbitrary locations within the flow field and yields data which can be used to judge the applicability of various turbulence and mixing models.

The optical system employed for the temperature turbulence measurements is shown in Figure 2. A large field lens focuses the radiation on a narrow slit. To obtain good spatial resolution, the image of the electron beam is perpendicular to the slit. Light passing through the slit is collimated and split by a beam splitter. Light from the splitter passes through narrow band-pass interference filters and is focused on separate EMI 6256S photomultipliers. The narrow band pass interference filters are set to view separate spectral regions contained wholly within the (0,0) band of the N_2^+ first negative system.

The ratio of signals obtained from the filtered photomultipliers can be shown to be dependent only upon the molecular nitrogen

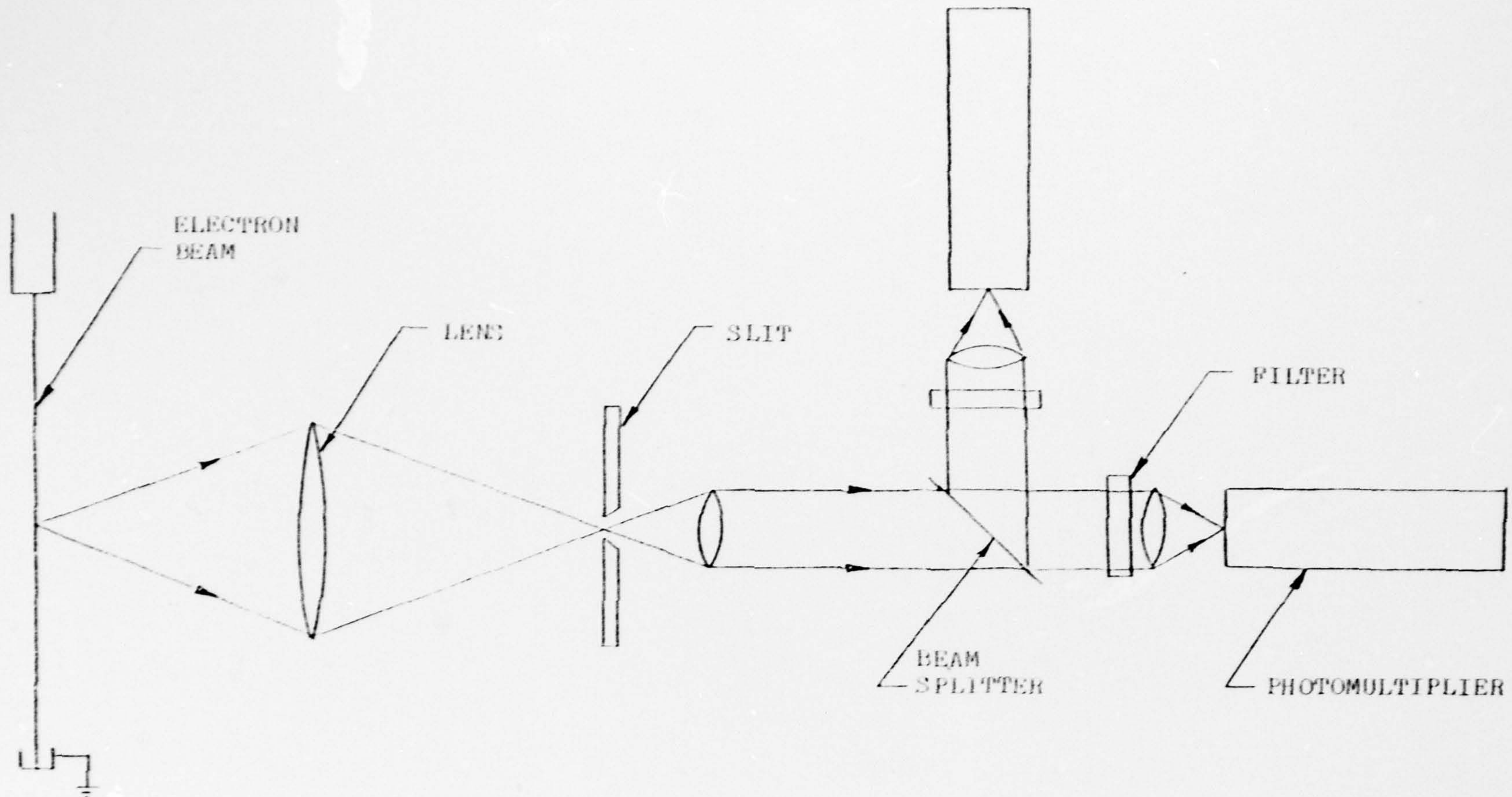


FIGURE 2. OPTICAL SYSTEM SCHEMATIC.

rotational temperature. The electrical system employed to measure the instantaneous ratio of intensities is shown in Figure 3. The photocurrents are obtained by measuring the voltage drops across load resistors in the anode circuits of the photomultipliers. The load resistor voltages are processed by operational amplifiers to reduce the output impedance of the circuits, thereby reducing the effects of electrical pick-up in the data cables. The resulting signals then enter variable gain, filtered amplifiers and separate sample and hold units. The outputs from the sample and holds are digitized by a fast A/D converter and stored in the central memory of the laboratory data acquisition system. The purpose of the sample and hold units is to allow data to be sampled from the two channels at the same instant of time (within a few nanoseconds).

To obtain accurate instantaneous rotational temperature measurements, the ratio of intensities from the two channels must be relatively free of the effects of random noise. With the experimental configuration used here, the principal source of noise is that due to random electron emissions within the photomultipliers (shot noise). The effects of shot noise can be reduced only by increasing the overall signal level.

To maximize the signal levels, a duoplasmatron beam generator system is employed. The generator employs a low pressure arc discharge to provide the electrons, which are accelerated and focused to form an electron beam with voltages up to 75 kv and beam currents in excess of 30 ma.

In addition to the rotational temperature turbulence studies, research is under way to apply the electron beam for measurement of vibrational temperature within the mixing region. The intent of these studies is to determine if certain spectral regions within the electron beam radiation can be isolated which respond primarily to vibrational temperature turbulence. The primary difficulty in measuring vibrational temperature oscillations is that the radiation intensities induced by the electron beam depend upon both the rotational and vibrational temperatures. While the effects of vibrational temperature fluctuations can be removed from the rotational temperature data by properly choosing the spectral regions of observation, it is not clear that similar methods can be developed for removing the effects of rotational temperature fluctuations on vibrational temperature measurements. However, if such techniques can be developed this aspect of the research can have large impact on supersonic mixing lasers. Since lasing in these devices occurs between vibrational energy levels in a given electronic energy state, knowledge of the magnitude and frequency content of the vibrational temperature turbulence should give direct indication of the oscillations to be expected in the laser output.

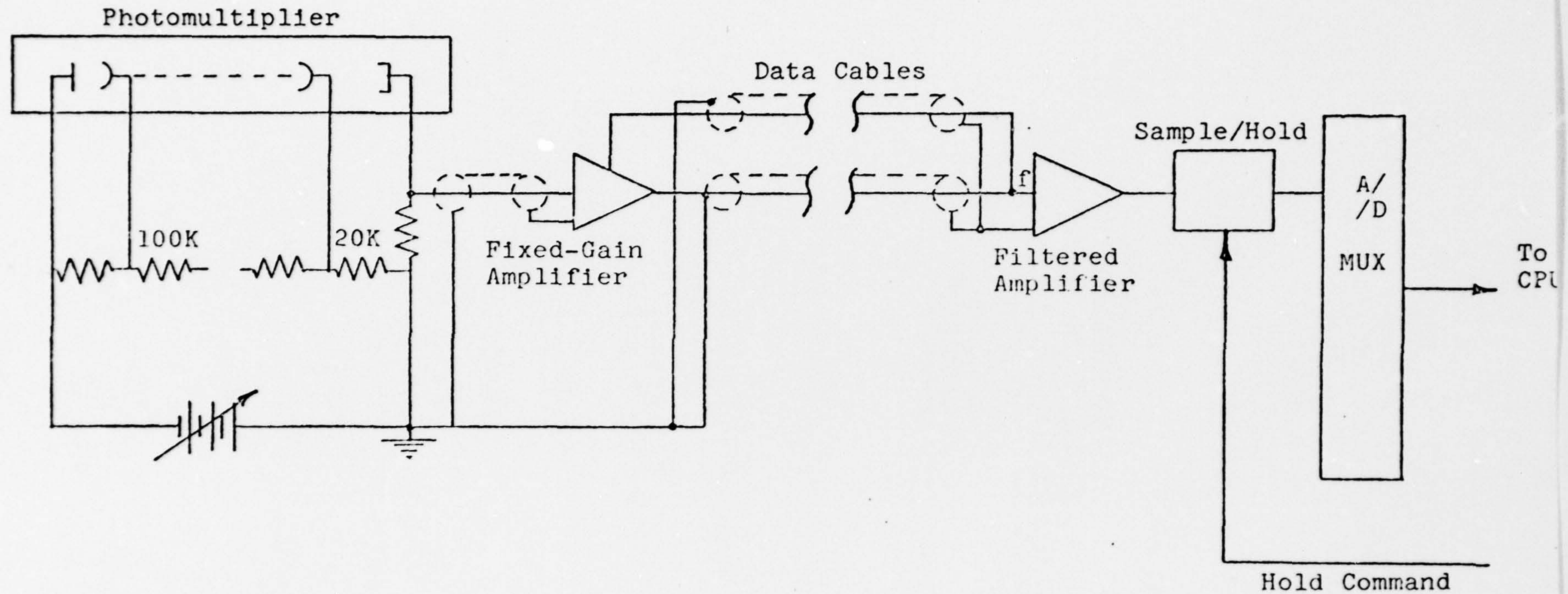


FIGURE 3. ELECTRO-OPTICAL SYSTEM SCHEMATIC

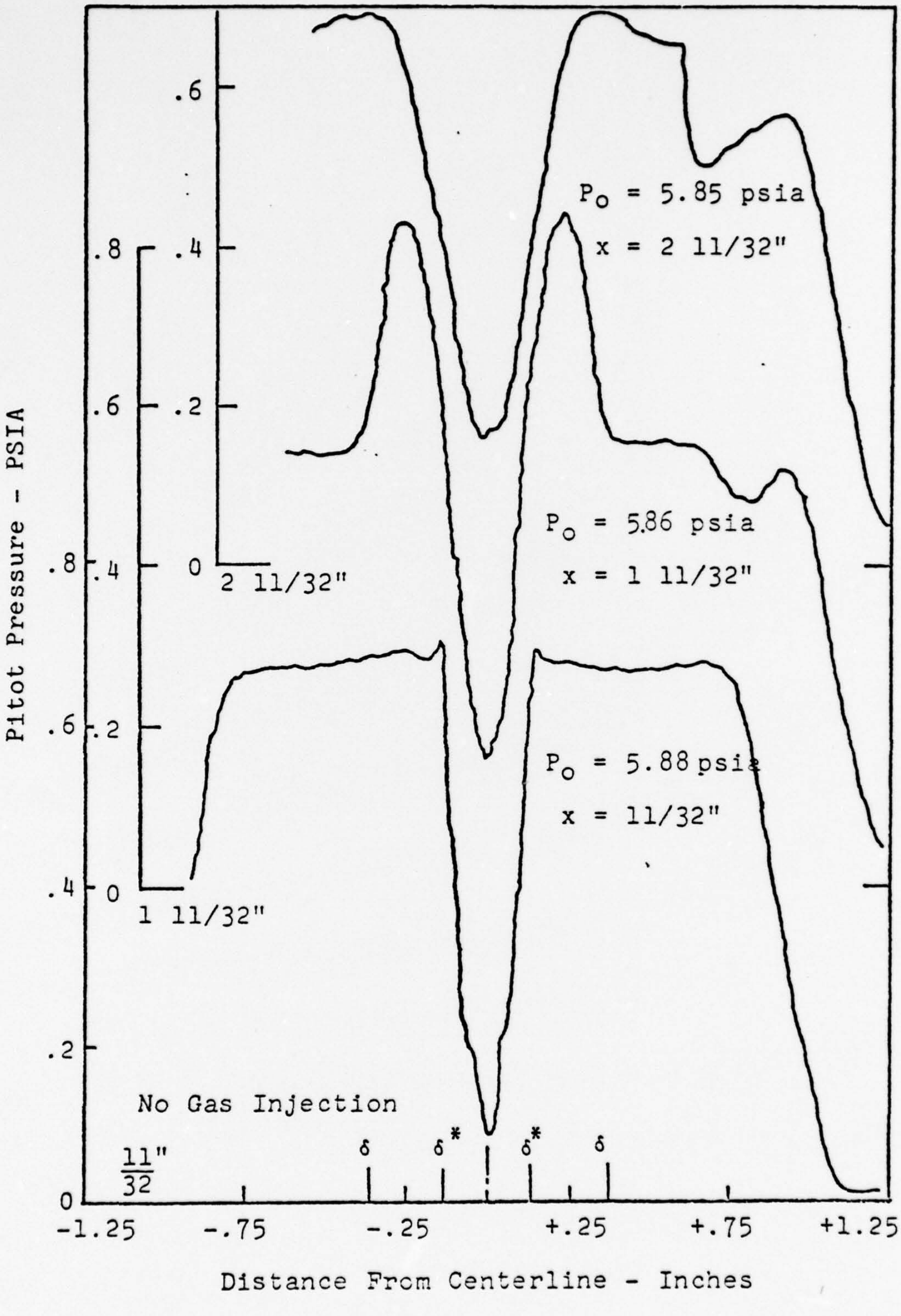


FIGURE 4. TYPICAL PITOT PRESSURE PROFILES;
x = DISTANCE DOWNSTREAM OF NOZZLE EXIT.

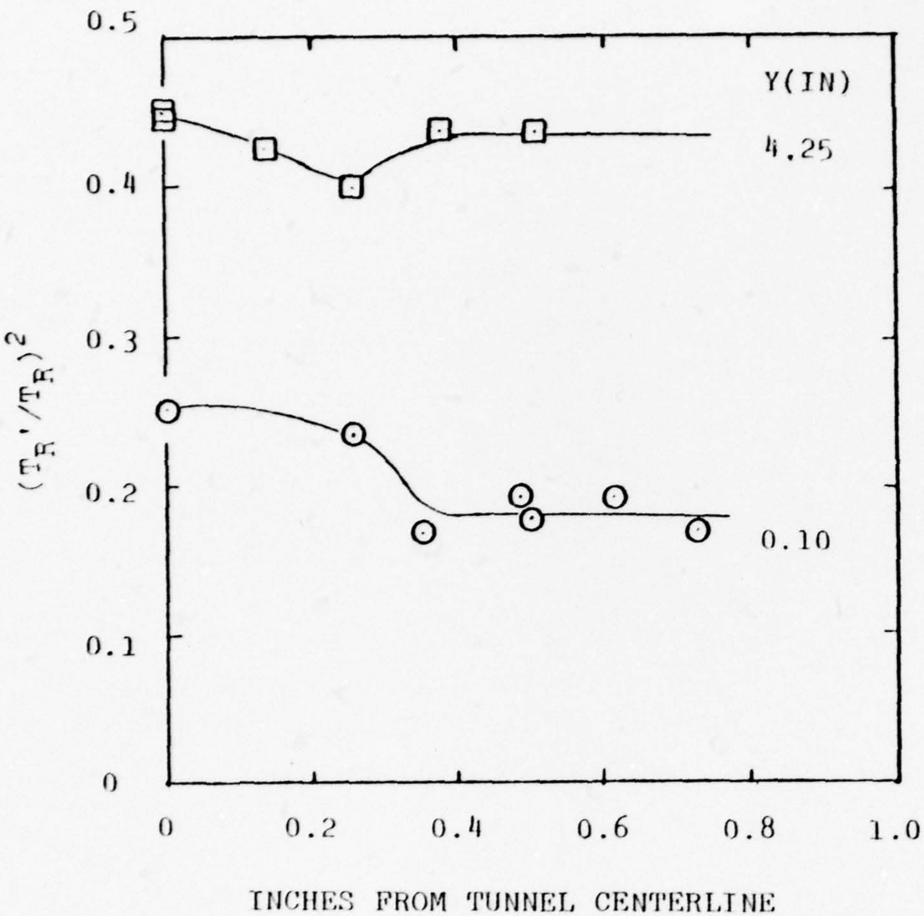


FIGURE 5. ROTATIONAL TEMPERATURE FLUCTUATIONS

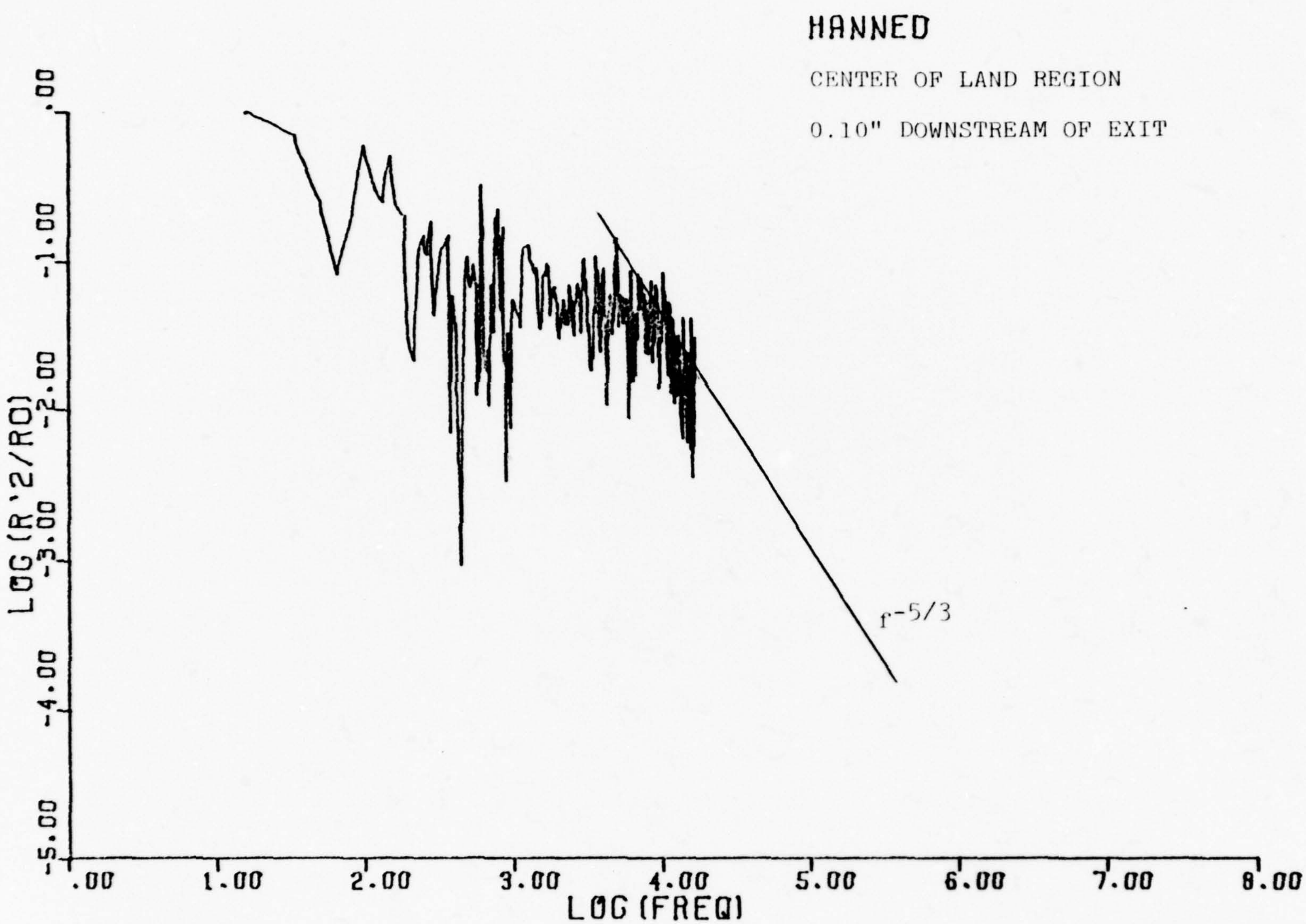


FIGURE 6. POWER SPECTRAL DENSITY

In addition to the electron beam, conventional pitot pressure and mass flow probes are also used to examine the mixing region. Preliminary studies have also been conducted to examine the applicability of the Laser Doppler Velocimeter (LDV) in the arc-heated flow field. These latter studies are in an early stage at this writing.

C. TYPICAL RESULTS

Data have been obtained from a variety of test configurations; typical pitot pressure, steady state rotational temperature, and rotational temperature turbulence data are shown in Figures 4-6. The complex structure of the flow field is evident in the pitot pressure surveys of Figure 4. When either contoured or wedge nozzles are used, a lip shock forms at the nozzle exit; however, the shock is much weaker with the contoured nozzles. At large distances downstream of the nozzle exit, the lip shock extends far into the inviscid flow region such that there is no region of uniform flow. This observation is confirmed by electron beam flow visualization photographs which show that the wave system generated by the required flow turning at the nozzle exit processes all of the gas seen by the probes and the electron beam. Hence, significant non-uniformities exist across the entire flow field at large distances downstream of the nozzle exit; placement of the laser cavity in this region could lead to much degradation in the quality of the output laser beam.

Typical broad-band rotational temperature fluctuations measured at two axial stations are shown in Figure 5. The mixing region is seen to contain the largest temperature fluctuations with the differences between the free stream and mixing layer fluctuations decreasing in the downstream direction. This is in basic agreement with steady state data which show that the overall gradients in flow properties across the mixing layer generally decrease as the distance downstream of the nozzle exit increases. It is also notable that relatively large temperature fluctuations are indicated in the free stream flow. The detailed origins of these fluctuations are presently under investigation and modifications to the electro-optical measuring system have been made to reduce the contribution of electronic shot noise to the final results.

A typical power spectral density plot obtained from the center of the mixing layer near the nozzle exit is shown in Figure 6. The principal power occurs at relatively low frequencies (1 kHz) and the high frequency region of the spectrum decreases with increasing frequency nearly like $f^{-5/3}$, typical of classical turbulence. Analysis of the turbulence data now being collected from the facility will allow more complete characterization of the turbulence characteristics of the mixing region. Time-resolved reservoir properties will be measured along with the mixing layer rotational temperature turbulence to isolate the relative effects of oscillation in the wind tunnel supply conditions. Cross-correlation analyses employing digital computer data reduction techniques based on Fast Fourier Transforms are being used in this phase of the studies.

III. THEORETICAL RESULTS

A. OVERALL METHODS

Numerical experiments have been performed with a computer program which is a result of an extensive analysis of comparative turbulence models conducted by Burggraf of OSU. The program is capable of calculating laminar and turbulent two dimensional compressible boundary layer flows along a body and in wakes and free shear layers. Heat transfer to the nozzle wall is included in the analysis and appears to be particularly important for nozzle flows where the boundary layer is subjected to very high heat transfer rates in the region near the nozzle throat. Additionally, mass diffusion of a binary mixture is permitted in the shear layer subject to the assumption of unity Lewis number.

Closure of the system of equations can be accomplished with a number of models. These include:

a. algebraic eddy viscosity model
b. a single transport equation model
c. a two equation model

In the single transport equation model, the eddy viscosity is formed from the product of an algebraic length scale and a velocity obtained from a solution of the turbulent kinetic energy equation. The method is an extension of Glushko's incompressible model. The two equation model is developed from an edddy viscosity which is formed from a velocity and length scale that are both described by transport equations. This model uses an energy equation and a dissipation rate equation expressed in terms of a pseudo-vorticity.

The computer program also allows examination of the effects of boundary layer initial conditions on the calculated properties in the mixing region. For example, the influence of the high gradients in the nozzle throat region are included by specifying realistic edge conditions for the boundary layer solution. In addition, the influences of nozzle wall temperature on the predicted temperatures in the mixing layer appear to be particularly important and are being investigated with the computer program.

Momentum integral techniques are also being used to characterize the overall features of the mixing region. The advantage of this method is that the many assumptions inherent in finite difference solutions are not required. Instead, an approximate unifying theory for laminar, transition and turbulent wake processes can be developed for application to both two-dimensional and axisymmetric geometries. Velocity and enthalpy profiles across the mixing region are obtained in terms of a velocity gradient parameter similar to the Pohlhausen pressure gradient parameter. Comparisons are being made between the theoretical results and those for a variety of laminar, transition and turbulent processes.

Comparisons of the experimental data with the results of the two-equation model are in progress at this writing and will be reported when available.

B. TYPICAL RESULTS

Typical theoretical temperature, velocity, Reynolds stress and turbulent kinetic energy profiles from the one-equation model are shown in Figures 7-10. The predictions apply for the test Reynolds number of 7380 and the contour plots start at the nozzle exit; the locations of the experimental measuring stations are indicated on the plots. As can be seen from Figure 7, the changes in the temperature profiles are most dramatic very near the nozzle exit where the effect of the nozzle wall temperature is most important. The turbulent kinetic energy (Fig. 10) increases continually in the downstream direction, indicating that transition to a turbulent shear layer probably does not occur within the field of observation.

The predictions of Figure 7 and 10 are compared with those from a higher Reynolds number case (2 million) in Figures 11 and 12. In this case, the marked changes in the shear layer properties are restricted to the region very near the nozzle exit and the turbulent kinetic energy reaches a maximum value early in the flow field. Hence, transition would be expected very near the nozzle exit.

The theoretical and experimental temperature profiles are compared in Figures 13-15. At the upstream measuring station (Fig. 13), the data compare favorably. However, at the middle measuring stations (Fig. 14), the theory over predicts the local temperatures by significant amounts. At the downstream station (Fig. 15), the magnitude of the temperature peak is predicted by the theory, but the experimental shear layer thickness is significantly greater than the theoretical estimate.

The effect of boundary layer initial conditions on the theoretical estimates are indicated in Figures 16-18. In these calculations, the upstream history of the boundary layer is ignored and the shear layer is assumed to begin from a flat plate boundary layer. As can be seen, the flat plate theory greatly over estimates the shear layer temperatures. Hence, when the calculations are performed accounting for the high pressure gradients and heat transfer rates in the nozzle throat region, the theoretical and experimental data agree well near the nozzle exit. However, in the shear layer, the one-equation model over estimates both the shear layer temperatures and thickness.

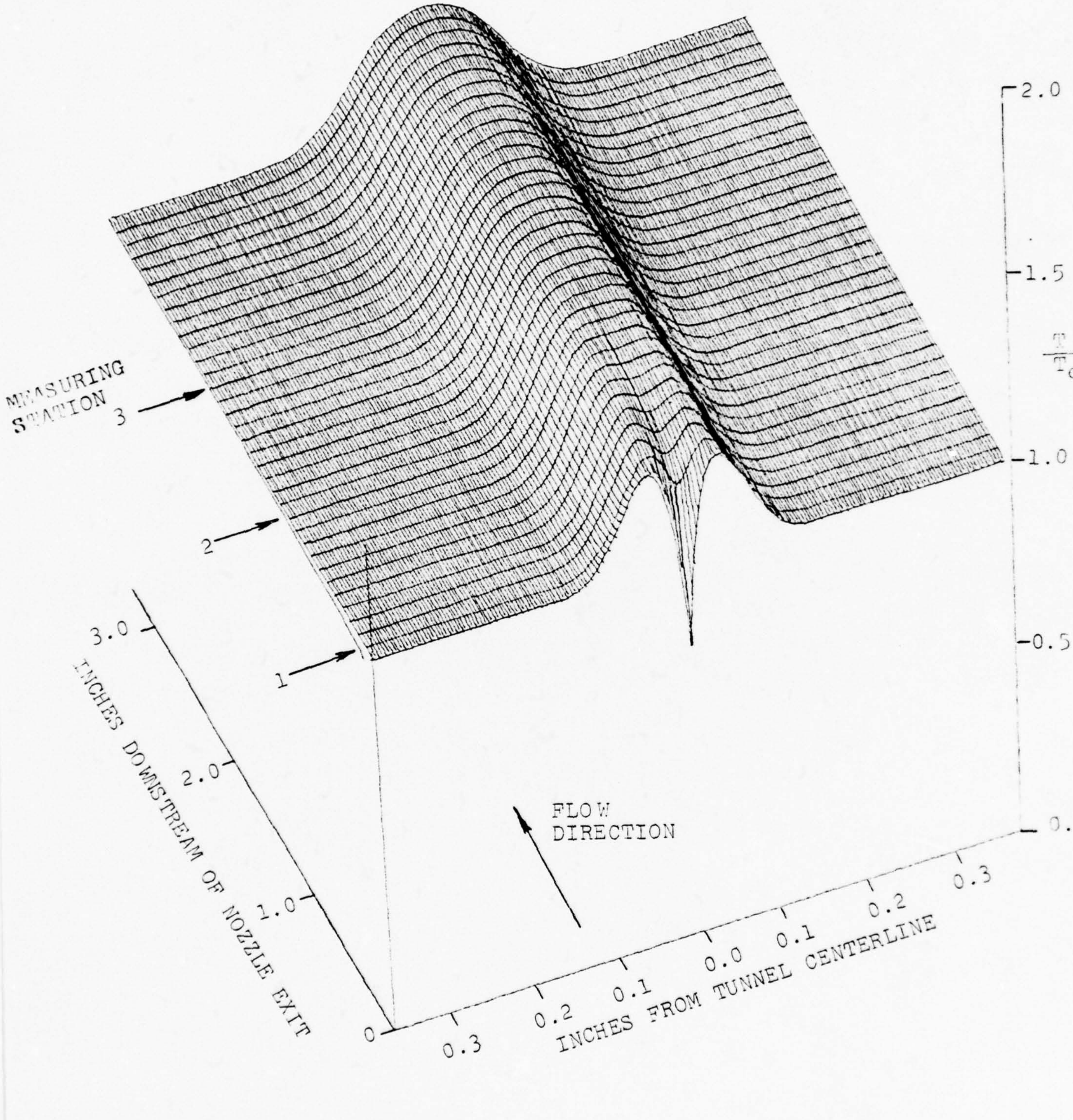


FIGURE 7. THEORETICAL TEMPERATURE PROFILES AT R_e = 7380.

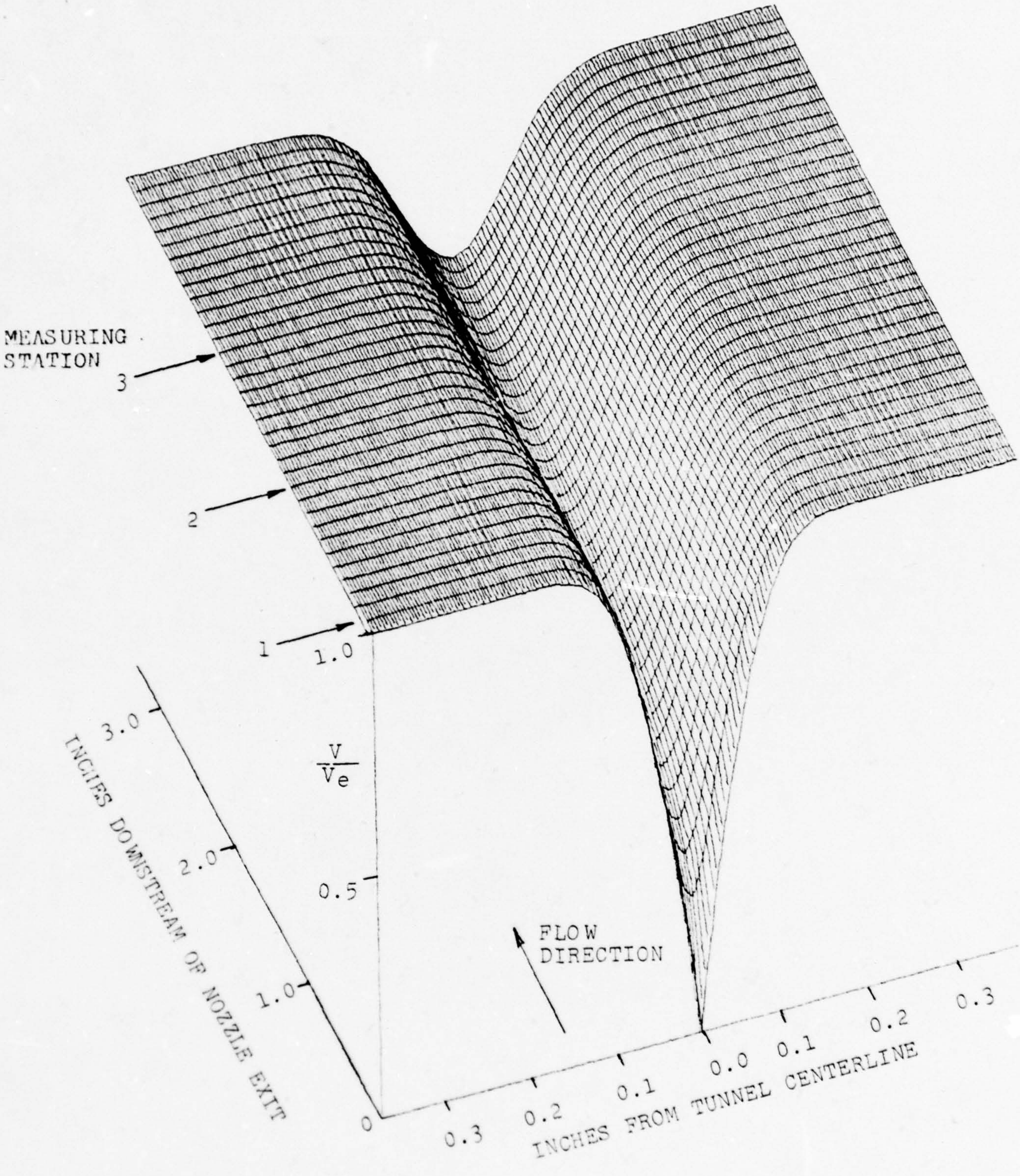


FIGURE 8. THEORETICAL VELOCITY PROFILES AT R_e = 7380.

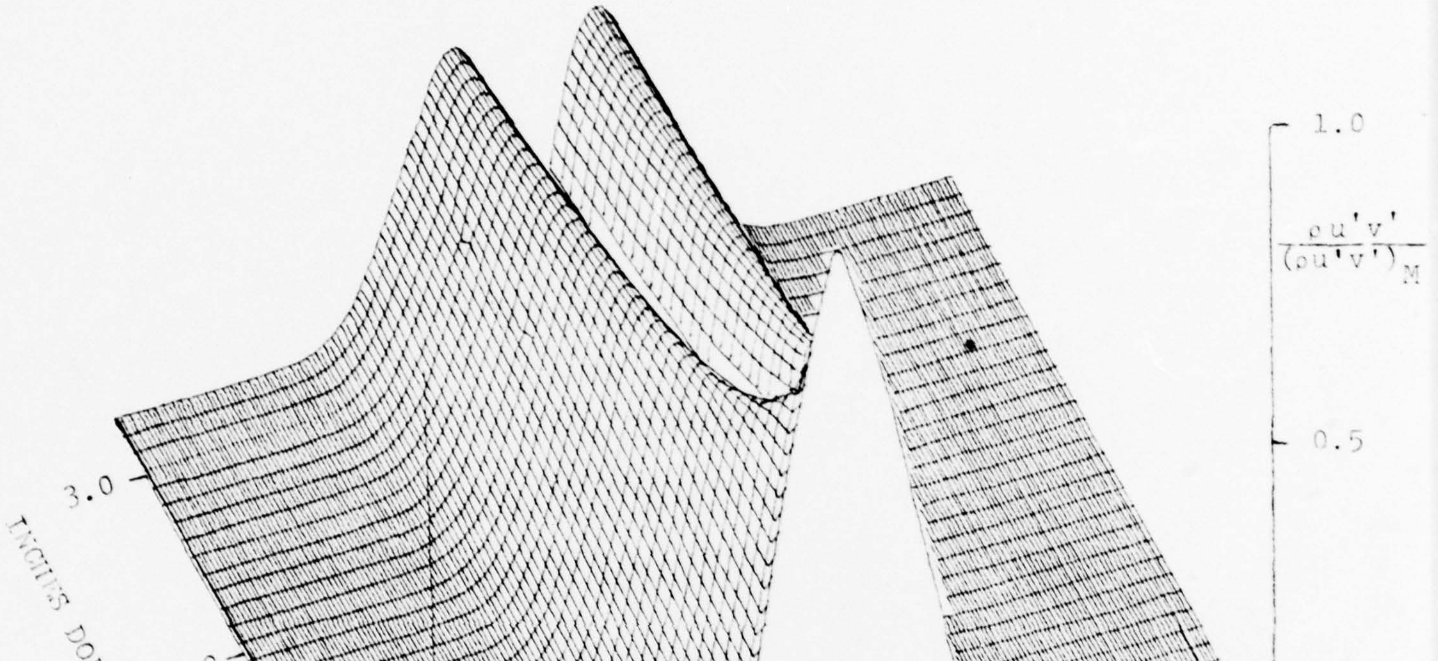


FIGURE 9. THEORETICAL SHEAR STRESS PROFILES AT R_e = 7380.

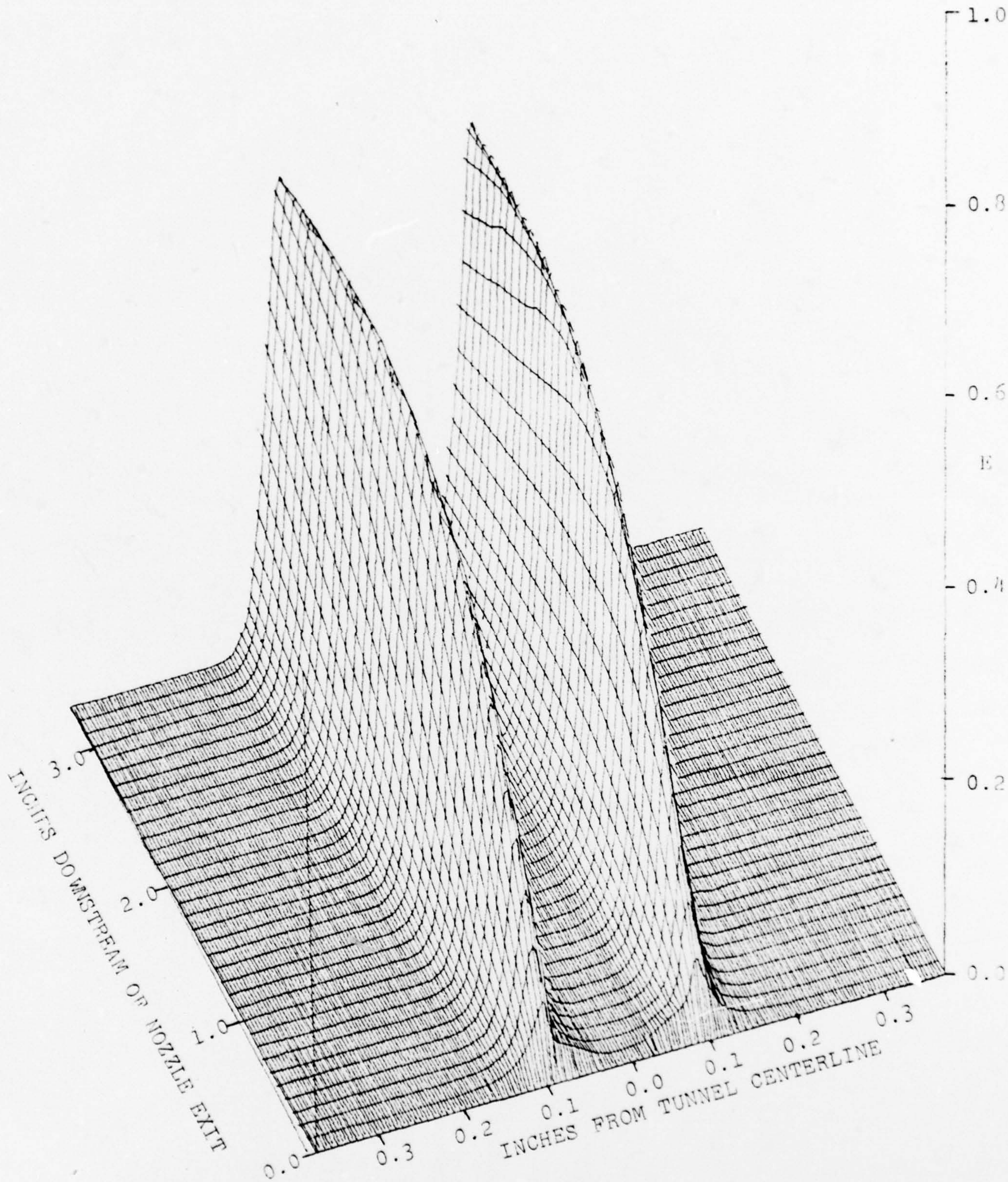


FIGURE 10. TURBULENT KINETIC ENERGY PROFILES AT R_e = 7380; E = K.E./u_e^2 x 103.

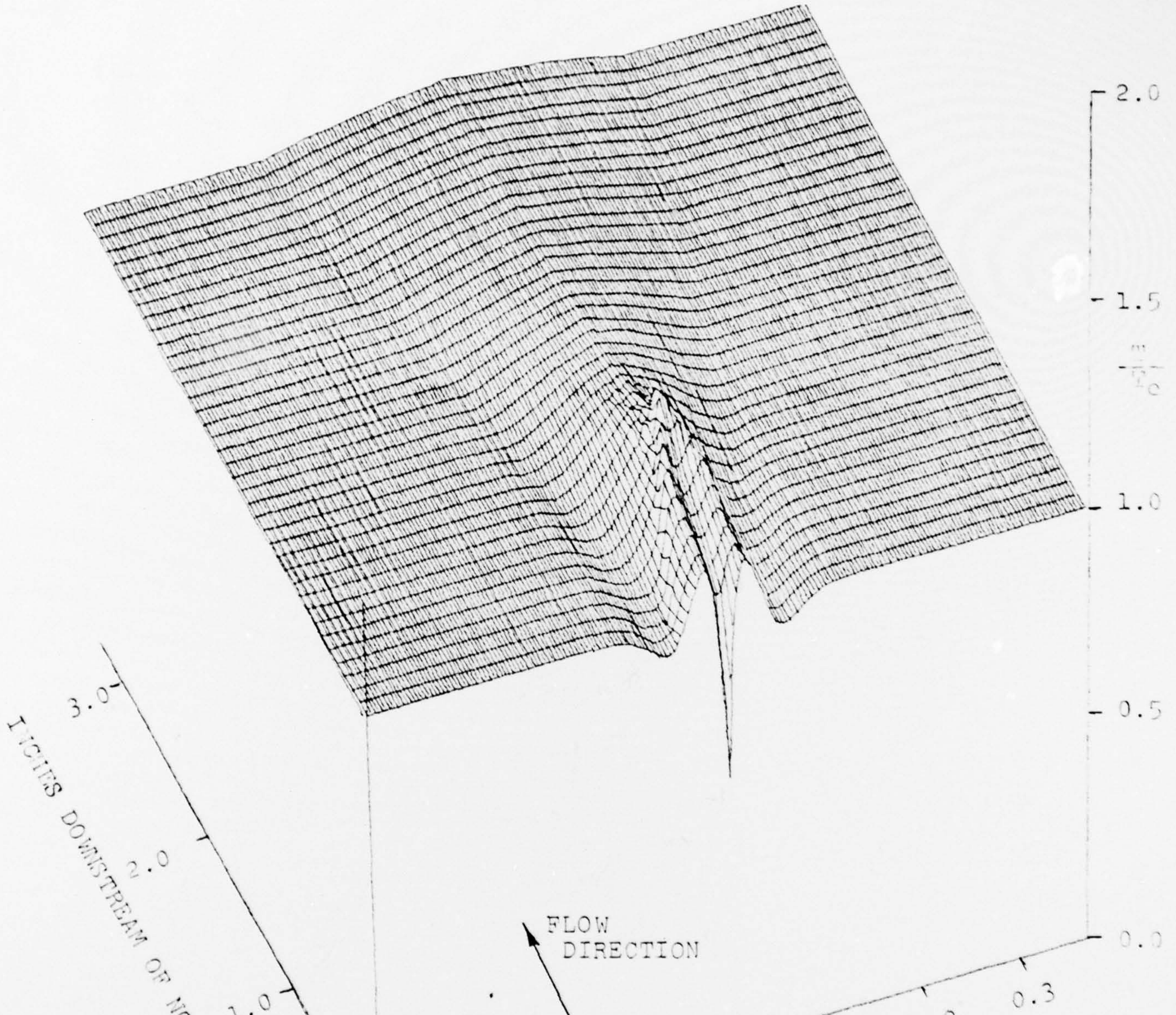


FIGURE 11. THEORETICAL TEMPERATURE PROFILES AT $R_e = 2.0 \times 10^6$.

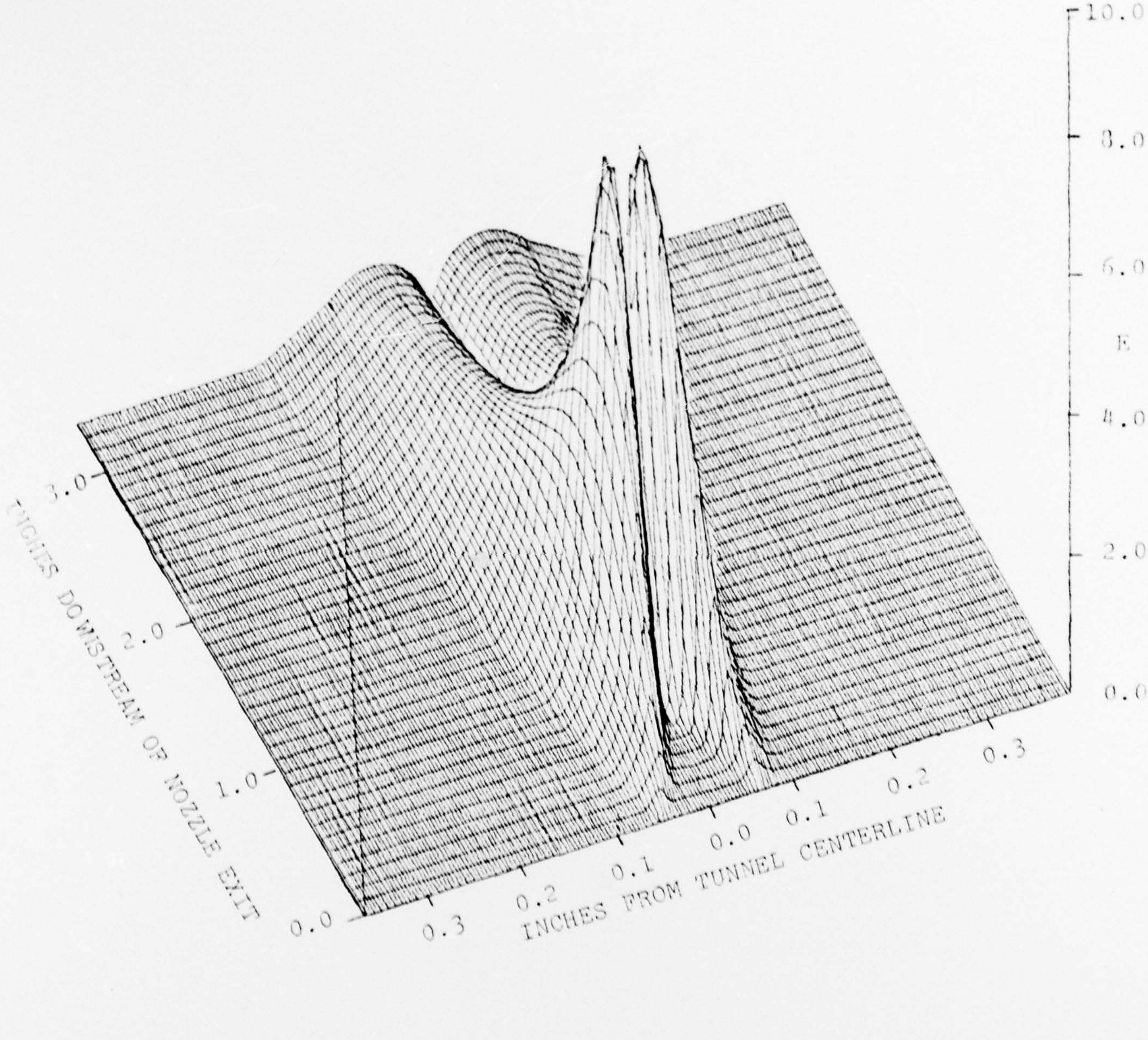


FIGURE 12. TURBULENT KINETIC ENERGY PROFILES AT $R_e = 2 \times 10^6$; $E = K.E./u_e^2 \times 10^3$.

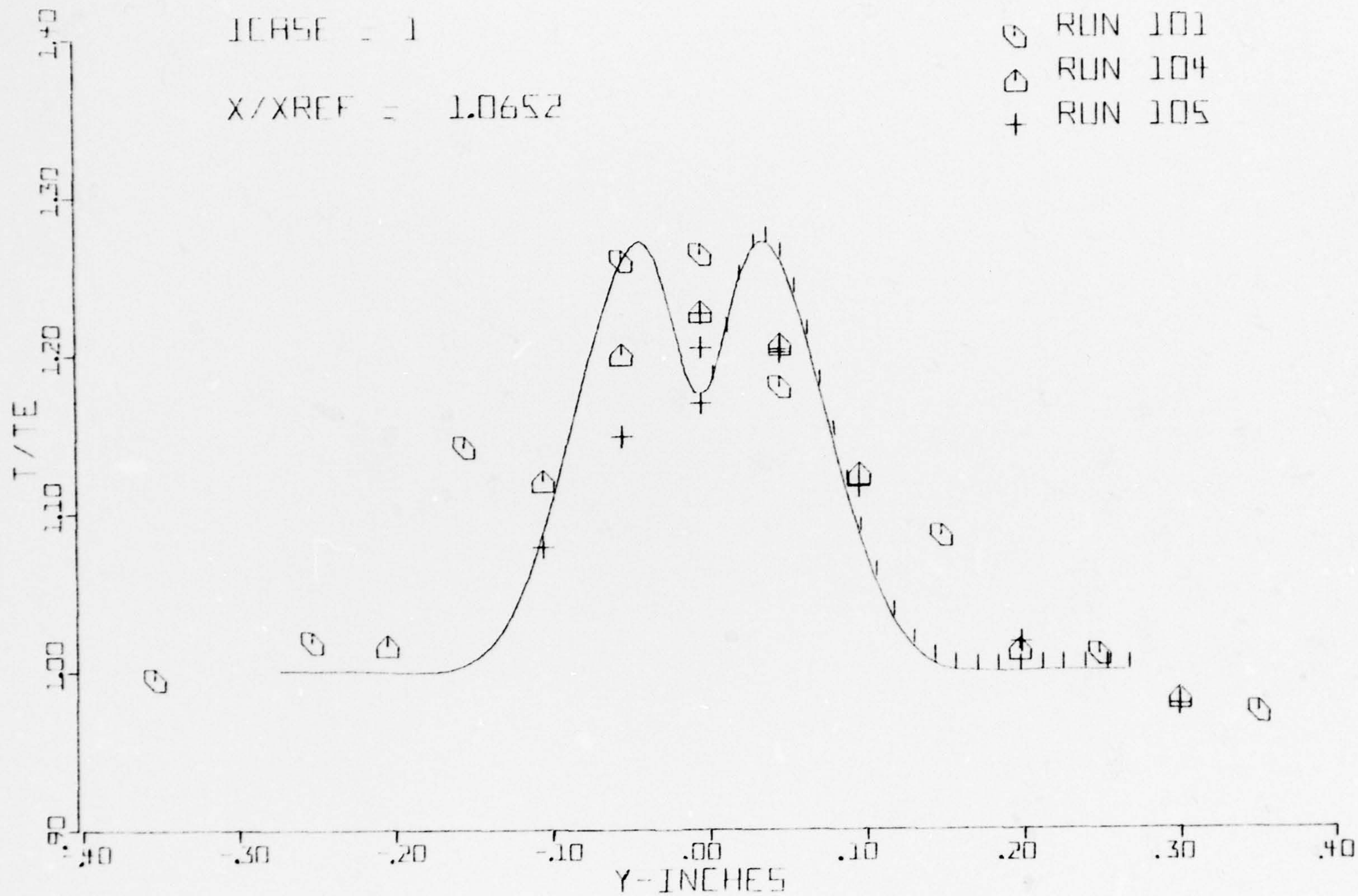


FIGURE 13. TEMPERATURE PROFILES AT 0.13 INCHES DOWNSTREAM OF NOZZLE EXIT: ——— THEORY AT R_e = 7380.

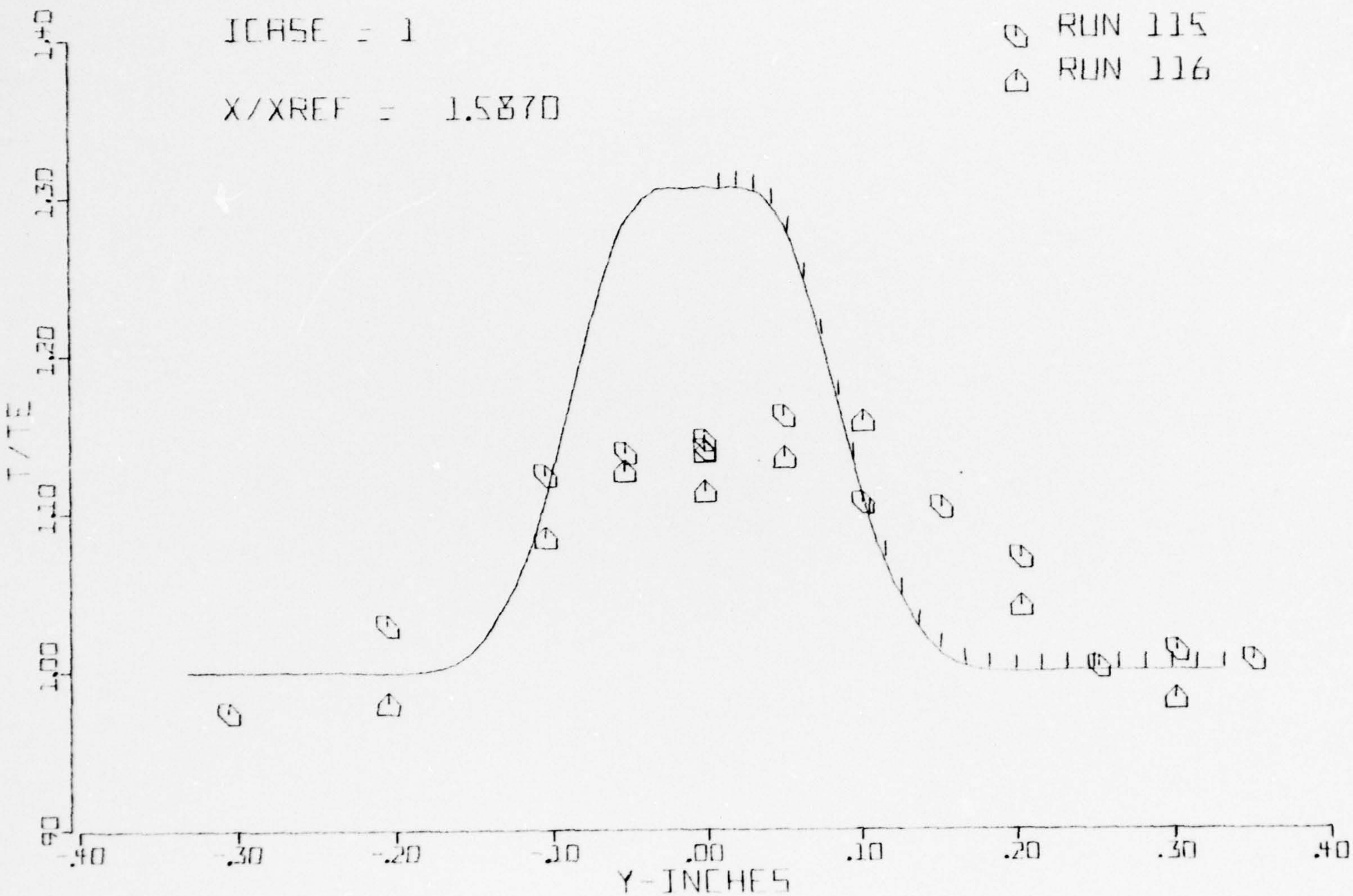


FIGURE 14. TEMPERATURE PROFILES AT 1.13 INCHES DOWNSTREAM OF NOZZLE EXIT: ——— THEORY AT R_e = 7380

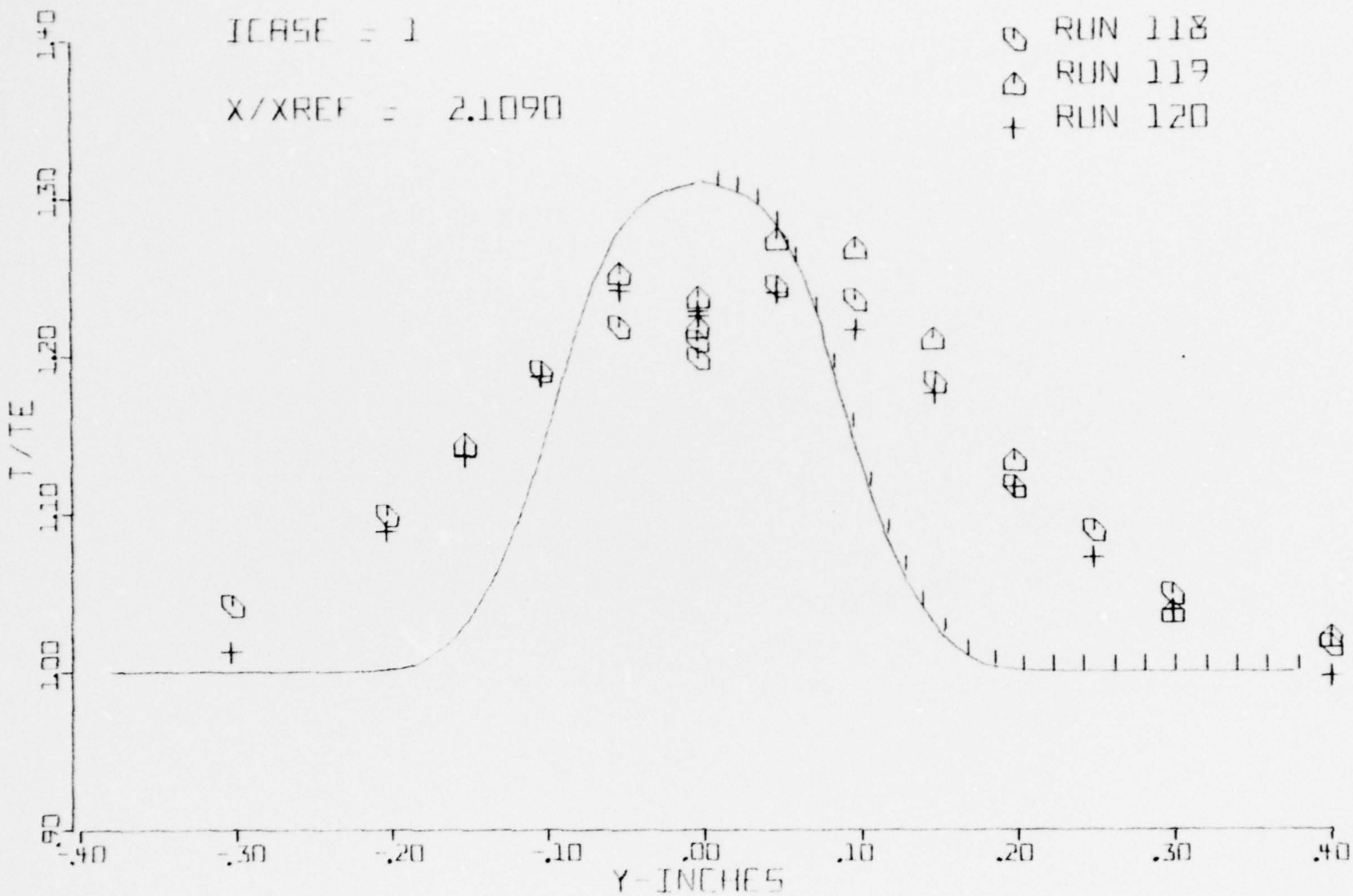


FIGURE 15. TEMPERATURE PROFILES AT 2.13 INCHES DOWNSTREAM AT NOZZLE EXIT: ——— THEORY AT R_e = 7380.

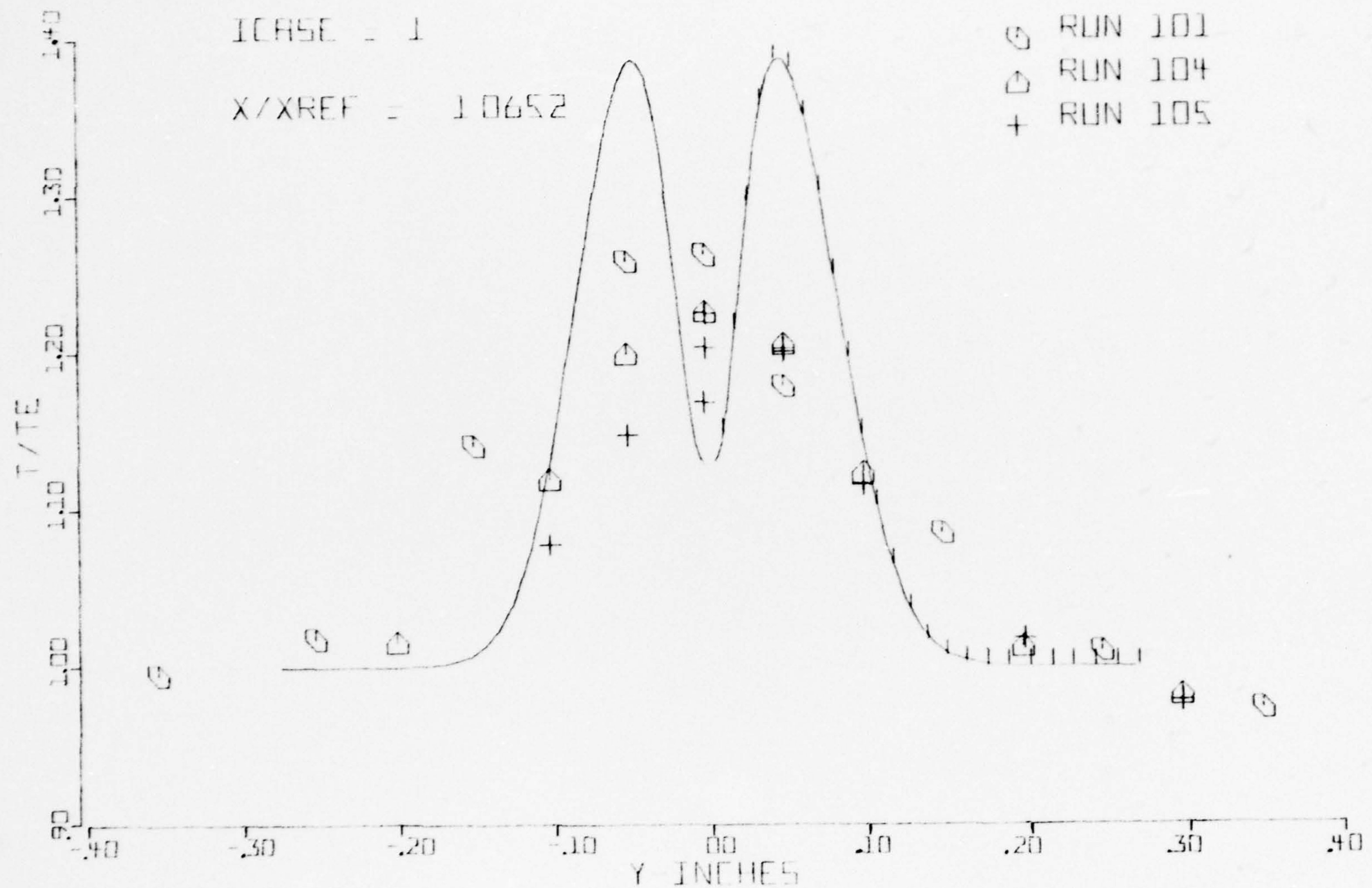


FIGURE 16. TEMPERATURE PROFILES AT 0.13 INCHES DOWNSTREAM OF NOZZLE EXIT; —— FLAT PLATE THEORY.

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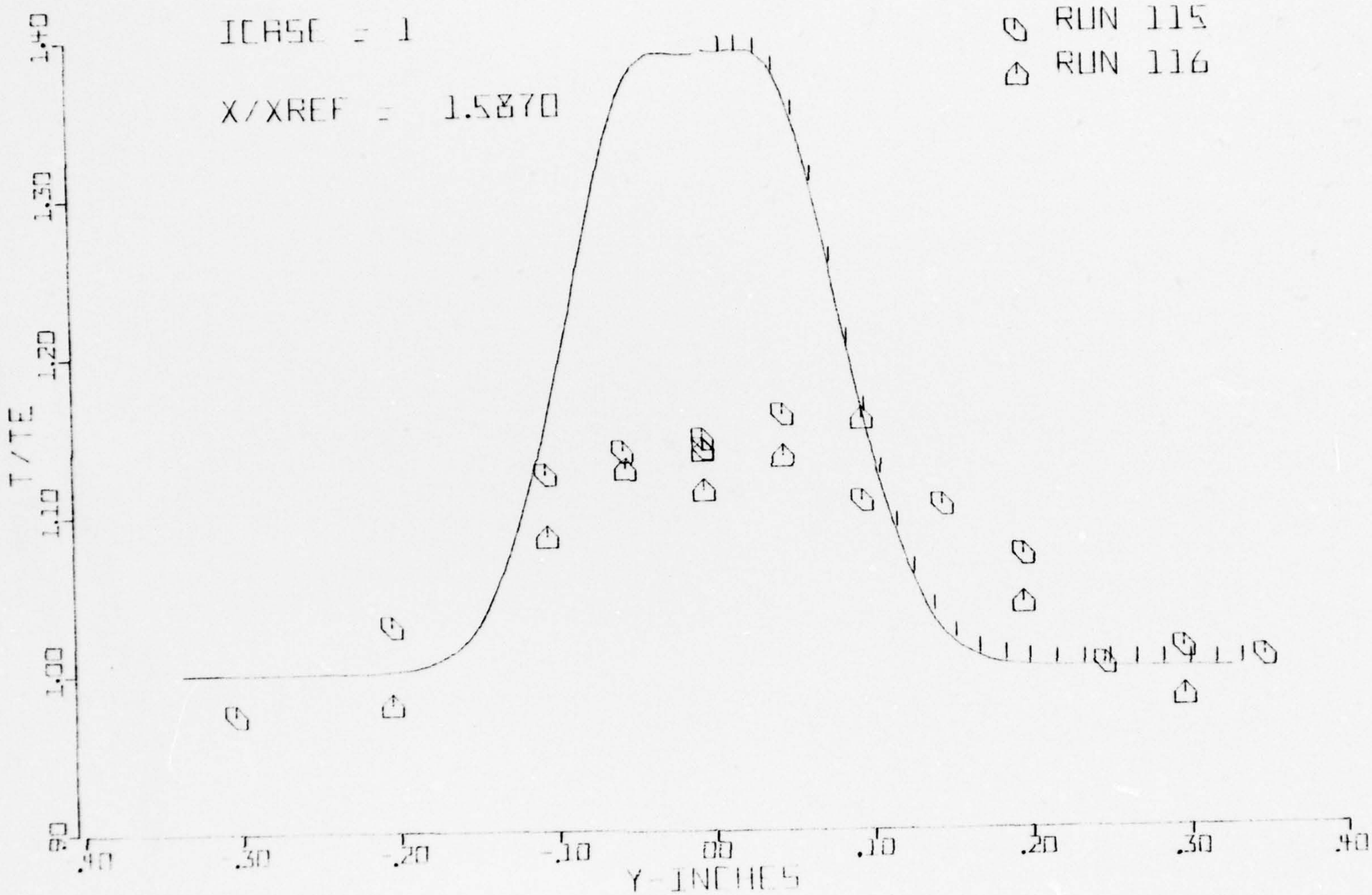

FIGURE 17. TEMPERATURE PROFILES AT 1.13 INCHES DOWNSTREAM OF NOZZLE EXIT: ——— FLAT PLATE THEORY.

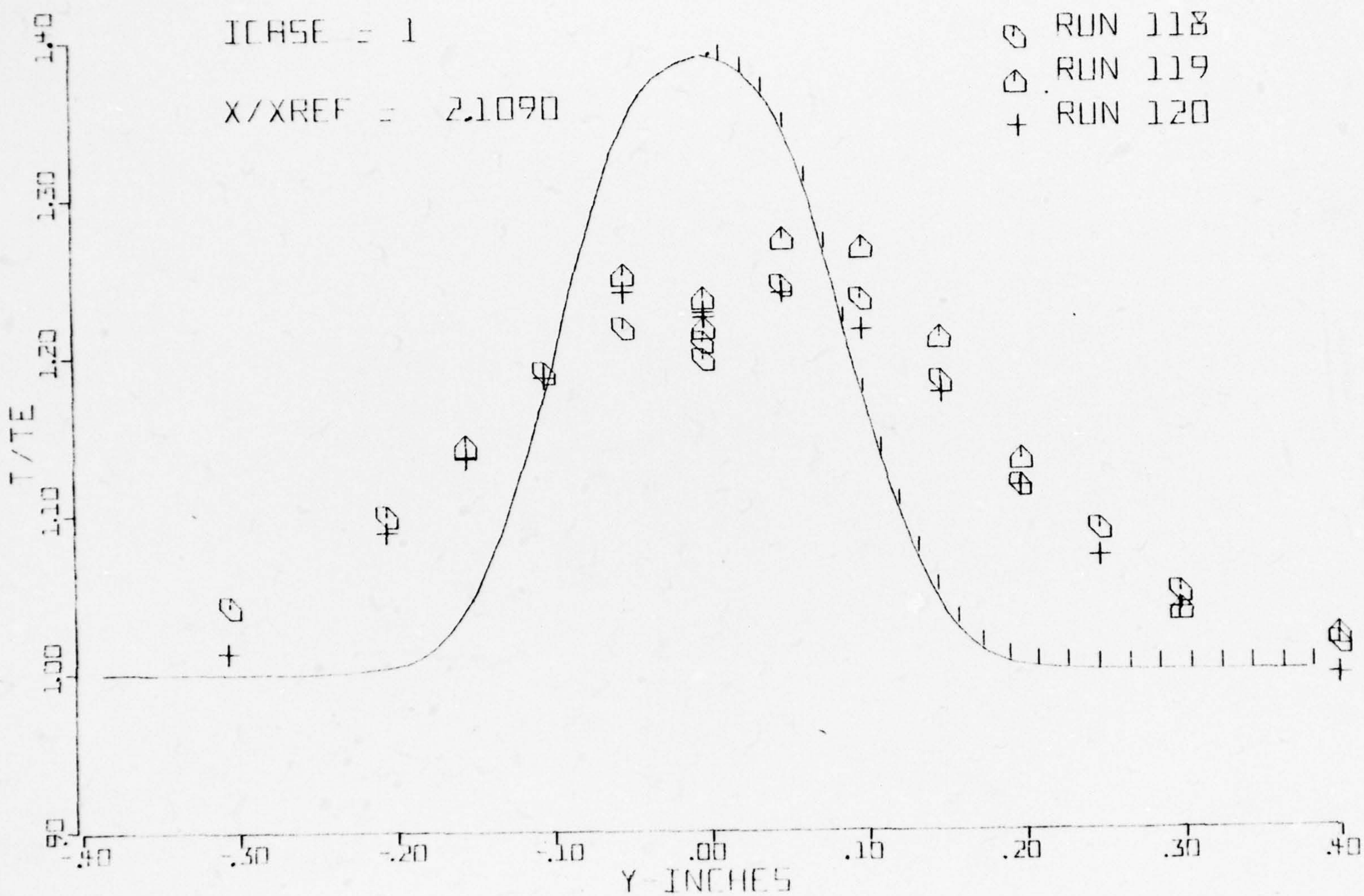

FIGURE 18. TEMPERATURE PROFILES AT 2.13 INCHES DOWNSTREAM OF NOZZLE EXIT: ——— FLAT PLATE THEORY.

IV. APPLICATIONS TO AFWL PROGRAMS

A. HIGH DENSITY ELECTRON BEAM STUDIES

For the last several years there has been an increased awareness of the need to perform detailed measurements of flow properties within lasing cavities. Ideally, such measurements should be made without perturbing the overall thermo-chemical state of the flow field. For example, in a CO_2 Gas Dynamic Laser (GDL) the very efficient energy transfer between the asymmetric stretch mode of CO_2 and N_2 is responsible, in part, for the population inversion which leads to lasing in the N_2-CO_2-H_2O GDL. The vibrational relaxation of N_2 within the flow field is relatively slow so that the resonant transfer between N_2 and the ν_3 mode of CO_2 leads to an elevated population of the (001) level of CO_2 compared to that of (100) level. To investigate the energy budget within the expansion, detailed measurements of the vibrational population distributions of the various species are required. Such distributions for CO_2 and H_2O can be investigated by measuring the intensities of the vibration-rotation bands emitted by these molecules. However, since N_2 is homonuclear, it has no pure vibration-rotation spectrum and some other means, such as an electron beam, must be used to investigate the N_2 vibrational population distribution.

Most measurements with electron beams are made in flows with static pressures near a few Torr; however, GDL's operate with much higher static pressures. Since there is considerable interest (particularly at AFWL) in making direct measurements of the vibrational temperature of N_2 in actual GDL flow fields, techniques for applying the electron beam to high density mixtures of N_2, CO_2 and H_2O were investigated. The CO_2 concentrations in air were varied from 0 to 25% (by volume) and the H_2O concentration was varied from 0 to 1%. Equivalent pressures ranged from 2 to 20 Torr. (Equivalent pressure is defined as the pressure corresponding to the actual gas density at a translational temperature of 300°K). Actual static pressures in the test gas exceeded 60 Torr.

The measured N_2 vibrational temperatures were compared with the results of theoretical analyses employing a 3-temperature model for the vibrational relaxation. Over the entire range of gas conditions and mixture ratios examined, good agreement between the predicted and measured vibrational temperature was obtained. This indicates that neither the high density, nor the addition of either CO_2 or H_2O caused measurable perturbations in the electron beam induced radiation in the N_2^+ first negative system. Hence. accurate vibrational temperatures can be measured in typical GDL gas mixtures with no loss in accuracy for equivalent pressures at least up to 20 Torr. This conclusion applies so long as there is a relative high flow velocity such that long lived metastable particles are swept out of the region of observation.

B. AFWL HIGH DENSITY ELECTRON BEAM GENERATOR

Based on the results discussed above, a high density electron beam generator and associated instrumentation were assembled for use in the combustion driven CO_2 GDL facility at AFWL (intermediate Test Facility, ITF). The overall system was designed to operate with gas densities up to those corresponding to an equivalent pressure of 50 Torr. In addition, an electro-optical system capable of scanning 150Å in 32 milliseconds was assembled for analysis of electron beam induced radiation. The operation of the electron beam generator and optical system were established in a static test chamber at OSU and subsequently installed at AFWL. Demonstrative tests were conducted by OSU personnel to instruct AFWL personnel in proper operation of the system.

The instrumentation system employed an Optical Multichannel Analyzer (OMA) fitted with a silicone vidicon and an optical system capable of recording 500 data points over a wavelength range of approximately 150Å. The OMA processes, displays, and signal averages optical data from all 500 channels simultaneously, and in real-time. Theoretical predictions of the vibrational band intensity distributions to be expected from the OMA were conducted to allow accurate determination of vibrational temperature from the measured spectra.

C. ATOMIC FLUORINE STUDIES

There is much current interest in determining the distribution of atomic fluorine throughout the flow field in supersonic HF and DF chemical lasers. If the fluorine concentration distribution could be measured in such systems, valuable information regarding the mechanisms active in the thermo-chemical mixing process could be obtained. In addition, more reliable data on the appropriate reaction kinetics and the effects of wall recombination would be available. Up to this time, no direct means of measuring the fluorine atom concentration has been developed, particularly for flow systems typical of chemical lasers. During the course of this research, preliminary demonstration of a new technique for determining the F atom concentration distributions in arbitrary flow fields was demonstrated. This new technique employs a high current electron beam and can be employed in chemical laser flows, even while lasing is occurring.

Calibration experiments were conducted in the arc heated wind tunnel with air as a test gas and SF_6 was admixed with the arc heated gas in the reservoir. The SF_6 mass flow rate was varied to provide fluorine atom fractions from 0 to 12% by volume. Various fluorine lines were observed in the electron beam induced radiation. The strongest line corresponds to the $3p^2P$-$3s^2P$ transition at 7037.5Å. Calibration data were collected for this line for F atom concentrations up to 1.6×10^{15} cm^{-3} and the data

are displayed in Figure 19. The good linearity of the line intensity indicates that it can be used as an accurate measurement of the fluorine concentration.

Results of these preliminary calibrations demonstrate that an electron beam can be used for direct measurements of the F atom concentration in certain gas mixtures and that measurements should be possible even under lasing conditions. However, before the method can be applied to fluorine with confidence, detailed calibrations of the line intensity variation with atom concentration must be performed. In addition, these calibration experiments should be performed in mixtures more typical of those in HF and DF chemical lasers. Such calibration experiments may be performed at AFWL in the near future.

V. PUBLICATIONS

The publications resulting from the experimental and theoretical research conducted to date are listed below.

1. Komar, J. J., "Investigation of Fluid Dynamic Interactions Within Multiple Nozzle Arrays," Ph.D. dissertation, The Ohio State University (1975).

2. Petrie, S. L., "Turbulence Measuring Techniques With an Electron Beam," paper presented at the 6th International Congress on Instrumentation in Aerospace Simulation Facilities, Ottawa, Canada, September 1975.

3. Petrie, S. L., and Komar, J. J., "Experimental Studies of Supersonic Mixing Laser Configurations," paper presented at 43rd Semiannual Meeting of the Supersonic Tunnel Association, 1 April 1975.

4. Komar, J. J., and Petrie, S. L., "Investigation of Fluid Dynamic Interactions Within Multiple Nozzle Arrays," paper presented at 9th AIAA Fluid and Plasma Dynamics Conference, 14-16 July 1976, to be submitted for publication in AIAA Journal.

5. Petrie, S. L., "Fluid Dynamic Interactions in Multiple Nozzle Arrays," paper presented to the Tri-Service Chemical Laser Symposium, 19-21 February 1975.

6. Petrie, S. L., "Vibrational Temperature Measurements at High Densities in $CO_2/N_2/H_2O$ Mixtures," paper presented at 44th Semiannual Meeting of the Supersonic Tunnel Association, Toronto, Canada, September 1975.

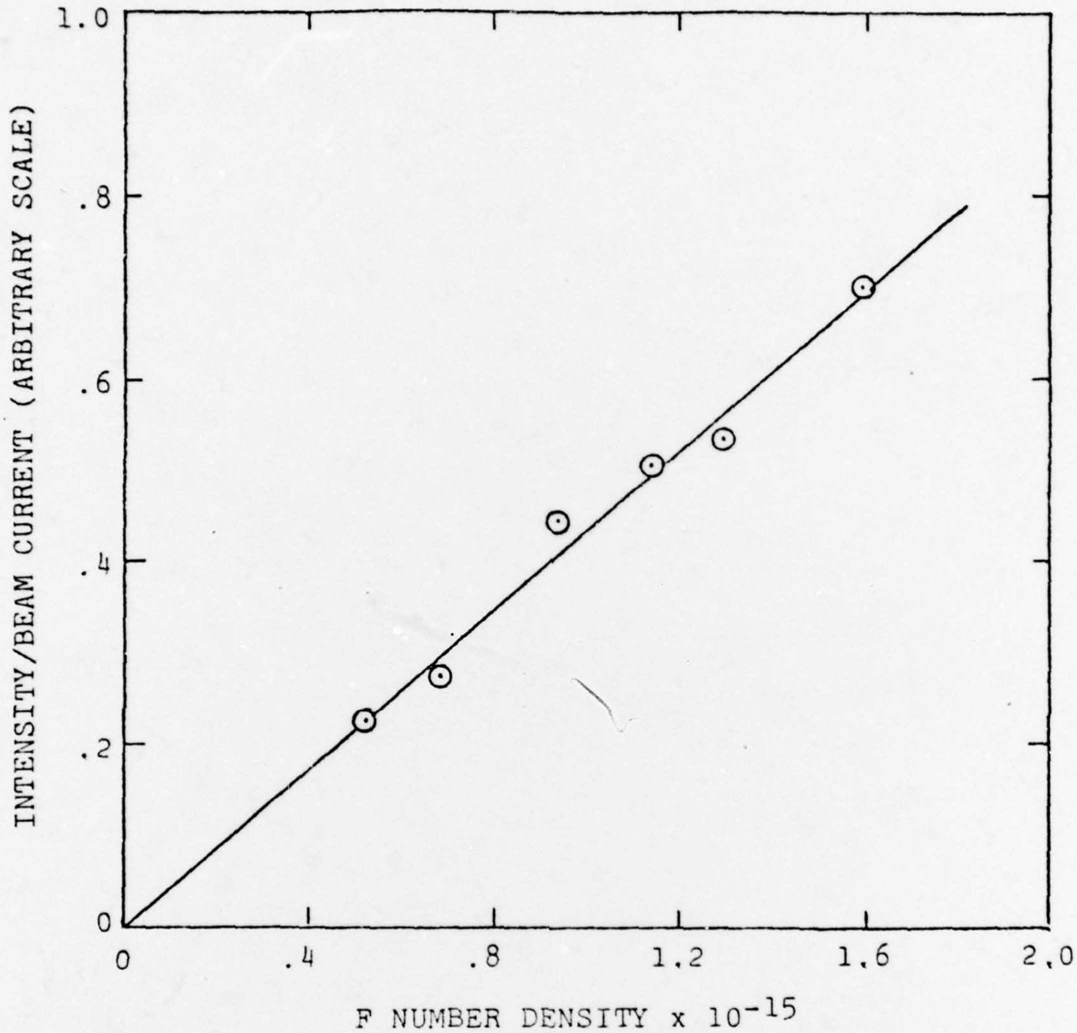

FIGURE 19. CALIBRATION OF $3p\,^2P-3s\,^2P$ (7037.5 Å) F LINE INTENSITY vs NUMBER DENSITY ⊙ DATA FOR p_o = 3 PSIA, T_o = 2360°K.

7. Petrie, S. L., "Electron Beam Diagnostics Applied to High-Density Gasdynamic Laser Mixtures," AIAA Journ. 15, 829 (1977).

8. Petrie, S. L., "Temperature Turbulence Studies in Supersonic Chemical Laser Configurations," Paper presented at Tri-Service Chemical Laser Symposium, 18-20 February 1976.

9. Korkan, K. D., Petrie, S. L., and Gasperas, G., "A Unified Theory to the Two-Dimensional and Axisymmetric Laminar, Transition and Turbulent Wake Processes Utilizing the Integral Technique," AIAA Paper 77-708, AIAA 10th Fluid and Plasmadynamics Conference, Albuquerque, N. M. (June 1977).

10. Gasperas, G., "Comparative Turbulence Modeling for Wall Boundary and Free Shear Layers in Supersonic Flow," Ph.D. dissertation, The Ohio State University (to be published).

Three Ph.D. students have been supported by this research. Dr. J. J. Komar completed dissertation research while Mr. G. Gasperas and Mr. D. Emmer are currently working on the grant.

VI. CONCLUSION

A variety of theoretical and experimental research has been conducted to examine the structure of mixing layers in co-planar supersonic flows typical of those in chemical transfer and gas dynamic lasers. The experimental facility is of relatively large size so that detailed measurements of the structure of the flow field can be made without extreme requirements on the spatial resolution of the measuring systems. Diagnostic techniques have been developed to measure the rotational temperature turbulence of molecular nitrogen, in addition to the usual steady state values of pressures, temperatures and density. In addition, preliminary experiments have been performed which demonstrate that an electron beam can be used for direct measurements of the concentration of atomic fluorine in chemical laser geometries.

An extensive theoretical analysis of the mixing region is in process. The numerical techniques allow examination of the effects of the turbulent model as well as those associated with the initial conditions in the nozzle boundary layer. The experimental configuration has been designed to duplicate the essential features of the mixing regions typical of gas flow lasers without the attendant complexities due to various injection geometries and complex chemical reactions. That is, the configuration stresses the fluid mechanical influences important in the mixing layers to permit assessment of the relative influences of parameters such as turbulence length scale, energy spectrum, temperature fluctuations, and density fluctuations.

Certain of the experimental techniques developed during the course of this research are being applied in actual laser flow fields at AFWL.